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Model Free Terminal Sliding Mode with Gravity Compensation: Application to an Exoskeleton-Upper Limb System

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Abstract**—**This paper deals with a robust model free terminal sliding mode with gravity compensation approach used to control an exoskeleton-upper limb system. The considered system is a 2-DoF robot in interaction with an upper limb used for rehabilitation. The aim of this paper is to control the flexion/extension movement of the shoulder and the elbow joints in presence of matched disturbances. In the first part, we present the exoskeleton-upper limb system modeling. Then, we controlled the considered system by the model free terminal sliding mode with gravity compensation. A stability study is realized. To prove the controller performance, a robustness analysis was needed. Simulation results are provided to confirm the robustness of the gravity compensation combined with to the Model free terminal sliding mode in presence of uncertainties.

Keywords**—**Exoskeleton-upper limb system, gravity compensation, model free terminal sliding mode, robustness analysis, Monte Carlo, H∞ methods.

I. Introduction

ABILITY to move upper limbs is very necessary to ensure the basic activities of human everyday life. The upper limb is characterized by its mobility and its ability to handle and grasp objects [1]. The inability to operate the upper limb, due to an accident, makes human life more complex. So, it is necessary to find a solution to help these people and improve their comforts.

Robotics naturally emerged in the field of upper/lower limb rehabilitation in the 1960s [4], [5], as an evolution of existing mechanical devices and in response to the need to improve the quality of treatments.

Rehabilitation robots are systems in physical interaction with humans used to encourage the subject's participation in the movement, even when assisted. They act as an amplifier that augment, reinforce or restore human performances. This interaction must then be fine enough to meet the requirements of human motor control and allow the establishment of controls dedicated to rehabilitation.

In literature, upper limb exoskeletons are utilized in different fields of applications. In the medical field, exoskeletons are used to perform basic activities of daily life for hemiplegics or for rehabilitation [6]. For military application, they are employed to increase the physical endurance of soldiers and to help them to lift heavy loads. Also, exoskeletons are used for assistance to dependent persons. A motorized exoskeleton can allow monitoring and robotic assistance of sports training (achieving the perfect gesture with adequate strength, speed and precision) [7].

With the use of exoskeletons distributed along the limb, it becomes possible to control not only the movements of the hand but one can also control the articular movements of the subject's arm [21]. This method makes it possible to approach the problem of neuromotor rehabilitation differently. Joint rehabilitation also allows better recovery in people with hemiparetics.

The objective of controlling an exoskeleton is to follow the movements of a healthy user. To achieve this goal, it is necessary to apply appropriate, performing and robust controllers. The dynamic of the exoskeleton-upper limb system is characterized by its complexity, so researchers developed many control laws like the sliding mode [10], the mixed force and position controller [11], universal approximations of fuzzy logic or neural networks approaches [12], adaptive control [24], etc.

Uncertainties and disturbances can influence the performance and the effectiveness of the applied controllers when tracking the desired trajectories. So, we are interested in the robustness study of the exoskeleton-upper limb system. The robustness test is important in order to identify the operating factors that are not necessarily studied during the development phase of the method, but which could have an influence on the results, and consequently to anticipate the problems that may occur at the moment of control application.

The contribution of this paper is to develop a robust Model Free Terminal Sliding mode algorithm with gravity compensation to control a 2-DoF exoskeleton-upper limb system. As a robustness study in presence of matched uncertainties, Monte Carlo and H∞ methods were used.

The paper is organized as follows: The modelling of the exoskeleton-upper limb system is presented in Section II. Section III deals with the control and the stability study. The robustness analysis of the considered system using Monte Carlo and H∞ methods is given in Section IV. In Section V, simulation and results are given. Finally, Section VI is kept for the conclusion and future work.

II. The Exoskeleton-Upper Limb System Modeling

To control the flexion/extension movement of the shoulder and the elbow joints of the exoskeleton-upper limb system, we start by modeling the considered system.

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The system is an exoskeleton in interaction with a human upper limb [13], [14] presented by Fig. 1.

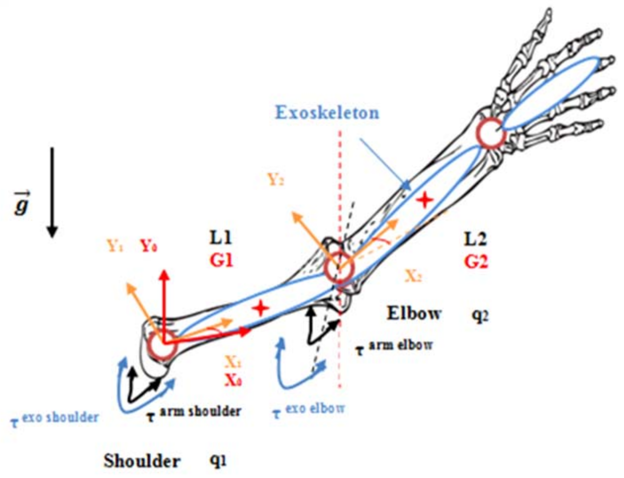

Fig. 1 General configuration of a 2 DoF exoskeleton-upper limb system

The kinematic model of the considered system is given by Fig. 2.

Referring to Euler Lagrange equation, the dynamic model of the system having two degrees of freedom (DoF) in the presence of friction is given by:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + f_v\, \dot{q} + k_i \mathrm{sign}(\dot{q}_i) = \tau^{exo} + \tau^{arm} + \tau^{ext} \quad (1)$$

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(q, \dot{q}) = \tau^{exo} + \tau^{arm} + \tau^{ext} \quad (2)$$

with $q \in \mathbb{R}^2$ present the joint positions vector; $\dot{q} \in \mathbb{R}^2$ is the joint velocities vector; $\ddot{q} \in \mathbb{R}^2$ is the joint accelerations vector; $M(q) \in \mathbb{R}^{2x\,2}$ is the inertia matrix; $C(q,\dot{q}) \in \mathbb{R}^{2x2}$ is the Coriolis matrix; $G(q) \in \mathbb{R}^2$ is the gravitational vector; $F(q,\dot{q}) \in \mathbb{R}^2$ is the force generated by friction; $\tau^{exo} \in \mathbb{R}^2$ is the control vector applied by exoskeleton; $\tau^{arm} \in \mathbb{R}^2$ is the torque applied by the human; $\tau^{ext} \in \mathbb{R}^2$ is the external torque; $F(q, \dot{q}) = f_v\, \dot{q} + k_i\, \mathrm{sign}(\dot{q}_i)$; $k_i\, \mathrm{sign}(\dot{q}_i)$ is the resistive torque due to dry friction; $f_v\, \dot{q}$ corresponds to the resistive torque due to the viscous friction of the human exoskeleton-arm system;

$$M(q) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix};\ C(q, \dot{q}) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix};\ G(q) = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}$$

where $\alpha = q_1 + q_2$; $l_1 = O_1G_1$; $l_2 = O_2G_2$; m_i are the exoskeleton joint mass; m_{ii} are the arm joint mass; l_{ii} are the arm joint length; I_{ii} are the arm joint inertia; $M_{11} = m_1\, l_1^2 + m_{11}\, l_{11}^2 + I_1 + I_{11} + (m_2 + m_{22})L_2^2$; $M_{12} = 2\, L_2\, (m_2\, l_2 + m_{22}\, l_{22}) \cos(\alpha - q_1)$; $M_{21} = 2\, L_2\, (m_2\, l_2 + m_{22}\, l_{22}) \cos(\alpha - q_1)$; $M_{22} = I_2 + I_{22} + m_{22}\, l_{22}^2 + m_2\, l_2^2$; $C_{11} = 0$; $C_{12} = -\dot{\alpha}\, (m_2\, l_2 + m_{22}\, l_{22})\, L_2 \sin(\alpha - q_1)$; $C_{21} = 0$; $C_{22} = \dot{q}_1\, (m_2\, l_2 + m_{22}\, l_{22})\, L_2 \sin(\alpha - q_1)$; $G_1 = [m_1\, l_1 + m_{11}\, l_{11} + (m_2 + m_{22})\, L_2]\, g \cos q_1$; $G_2 = [m_2\, l_2 + m_{22}\, l_{22}]\, g \cos \alpha$.

We developed then a control law used in order to get good desired trajectories tracking by the exoskeleton-upper limb system.

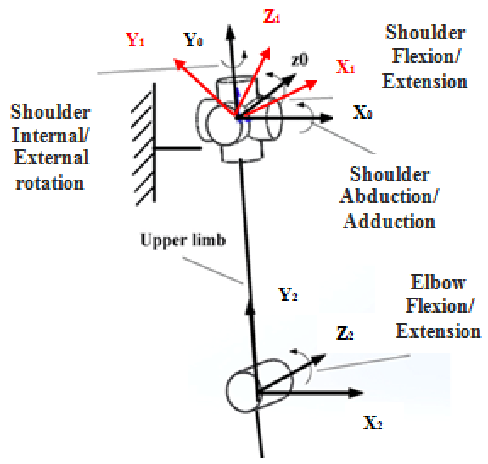

Fig. 2 Kinematic model of 2 DoF exoskeleton-upper limb system

The operating principle of the exoskeleton-upper limb system is described in Fig. 3. In the next sections, we suppose that $\tau^{ext} = 0$ and we consider $U = \tau^{exo} - \tau^{arm}$.

III. The Exoskeleton-Upper Limb System Control

In this section, we developed a control law in order to track the desired trajectories. So, a Model Free Terminal Sliding Mode with gravity compensation was proposed.

A. Gravity Compensation

Gravity compensation applied to robotics could avoid some problems. It acts as a corrector that only compensates for all of the forces that create the overshoot and the asymmetric transient behavior of the system. Also, the control with gravity compensation is able to reach the control objective in position globally for n DOF robots.

The use of gravity compensation is beneficial for robotic system which can be operated with relatively small actuators generating less torque [25].

In the literature, we find the use of two design approaches to obtain gravity compensation. The first approach is to use counterweights to compensate for the weight of the links. The counterweights can be mounted directly on the manipulator [26], [27], [8], [9].

The main advantage of this approach is the maintenance of the center of mass of the fixed mechanism for any given orientation of the gravity acceleration vector. This is particularly interesting when the manipulators have to operate with their base mounted in an arbitrary orientation.

The second approach is based on the storage of potential energy in elastic components such as springs. The advantage of this method is to add a smaller mass and inertia to the system. On the other hand, the resulting mechanism tends to be more complex: it can lead to mechanical interference and have a limited range of motion [27].

B. Model Free Terminal Sliding Mode Control with Gravity Compensation (MFTSMCGC)

The proposed control law consists in combining the Model Free (MF) with the Terminal Sliding Mode (TSM) using gravity compensation. The system control block diagram is shown in Fig. 4.

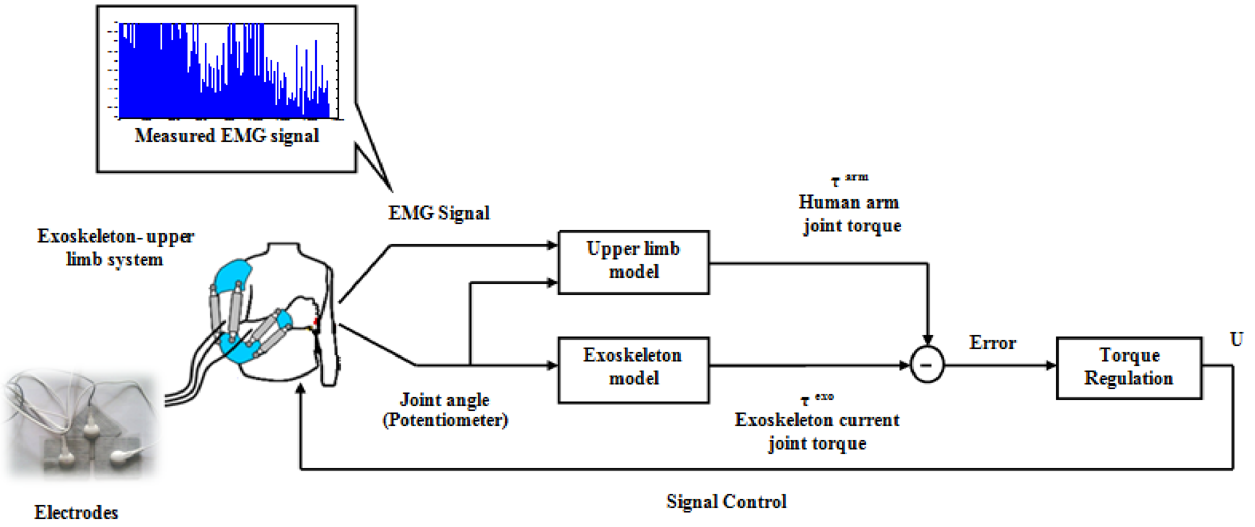

Fig. 3 The operating principle of the exoskeleton-upper limb system

The TSM has been developed by adding the non-linear fractional power element to the sliding surface to offer certain superior properties, such as the convergence in finite time of the state variables, faster and better tracking precision [28]-[30].

The MF control consists of a PID controller supplemented by compensation conditions provided by the online estimation of the system dynamics [19]-[21].

The MF controller is presented by [22], [23]:

$$\ddot{q} = F(t) + \alpha\, u_{MF}\,(t) \tag{3}$$

where q presents the output. F is an unknown nonlinear term including unmodeled dynamics and uncertainties. α is the input gain. u_{MF} is the corresponding input signal.

By closing the loop via the intelligent proportional-derivative controller (iPD), we get:

$$u_{MF} = - \frac{\hat{F} - \ddot{q}_d + u_c}{\alpha} \tag{4}$$

with u_c presents the feedback controller to track the desired output signal. q_d is a desired output trajectory. u_c is defined as the classic PD controller with:

$$u_c = K_D\, \dot{e} + K_p\, e \tag{5}$$

and:

$$e = q - q_d \tag{6}$$

with $e = q - q_d$ is the error of trajectory tracking. K_d and K_i are the PD's gains matrices. $\dot{q}_d$ presented the desired velocity. We get:

$$u_{MF} = - \frac{\hat{F} - \ddot{q}_d + K_D\, \dot{e} + K_p e}{\alpha} \tag{7}$$

From (3) and (4), we get:

$$\ddot{e} + u_c = F - \hat{F} \tag{8}$$

The estimation method is given as:

$$F(t) = \hat{F}(t) = F(t - \varepsilon) = \ddot{q}\,(t - \varepsilon) - \alpha\, u_{MF}\,(t - \varepsilon) \tag{9}$$

where ε is a small time delay.

According to the previous equations, we get:

$$\ddot{e} + K_D\, \dot{e} + K_p\, e = e_{est} \tag{10}$$

with: $e_{est} = F - \hat{F}$.

To remove the estimation error, the TSMC is combined with the MF control [12], and this gives the following MFTSMC:

$$U = u_{MF} + u_{TSM}$$

where u_{TSM} presents the TSM control law. u_{MF} presents the MF control law. We get:

$$U = - \frac{\hat{F} - \ddot{q}_d + K_D\, \dot{e} + K_p e}{\alpha} + u_{TSM} \tag{11}$$

We get:

$$\ddot{e} + K_D\, \dot{e} + K_p\, e = e_{est} + \alpha\, u_{TSM} \tag{12}$$

We considered the following system:

$$\begin{cases} x_1 = e \\ x_2 = \dot{e} \end{cases} \Longrightarrow \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = - K_D\, \dot{e} - K_p\, e + e_{est} + \alpha\, u_{TSM} \end{cases}$$

To ensure a fast follow-up of the desired trajectory, the surface in sliding mode is defined as [18]:

$$S_t = x_1 + \frac{1}{\beta} x_2^{r/s} \tag{13}$$

with: $\beta > 0$; r and s are positive odd integers satisfying the condition $r > s$.

We calculate $\dot{S}_t$:

$$\dot{S}_t = \dot{x}_1 + \frac{1}{\beta}\frac{r}{s} x_2^{(r/s)-1}\dot{x}_2 \tag{14}$$

We get:

$$\dot{S}_t = \dot{x}_1 + \frac{1}{\beta}\frac{r}{s} x_2^{(r/s)-1}\left(-K_D \dot{e} - K_p e + e_{est} + \alpha u_{TSM}\right) \tag{15}$$

We have:

$$u_{TSM} = u_{eq} + u_n$$

with: $u_n = -\frac{K}{\alpha}\,\mathrm{sign}(S_t)$

The function of the second term, called correction control, is to force the system's trajectories to achieve the sliding surface. u_{eq} is obtained when the condition $\dot{S}_t = 0$ is satisfied. So:

$$u_{eq} = -\frac{\beta s}{\alpha r}\dot{e}^{\,2-r/s} - \frac{K_D}{\alpha}\dot{e} + \frac{K_p}{\alpha} e \tag{16}$$

We get:

$$u_{TSM} = -\frac{\beta s}{\alpha r}\dot{e}^{\,2-r/s} - \frac{K_D}{\alpha}\dot{e} + \frac{K_p}{\alpha} e - \frac{K}{\alpha}\,\mathrm{sign}(S_t) \tag{17}$$

We obtain so:

$$U = -\frac{\beta s}{\alpha r}\dot{e}^{\,2-r/s} - \frac{\hat{F}-\ddot{q}_d}{\alpha} - \frac{K}{\alpha}\,\mathrm{sign}(S_t) \tag{18}$$

Using gravity compensation [16], the control law is written in the following form:

$$U = -\frac{\beta s}{\alpha r}\dot{e}^{\,2-r/s} - \frac{\hat{F}-\ddot{q}_d}{\alpha} - \frac{K}{\alpha}\,\mathrm{sign}(S_t) + G(q_d) \tag{19}$$

The system control block diagram is shown in Fig. 4.

To prove the stability of the considered system, we use the following Lyapunov function:

$$V = \frac{1}{2}\dot{q}^T M(q)\dot{q} + \frac{1}{2}S_t^2 \tag{20}$$

$$\dot{V} = \dot{q}^T M(q)\ddot{q} + \frac{1}{2}\dot{q}^T \dot{M}(q)\dot{q} + S_t\dot{S}_t \tag{21}$$

$$\dot{V} = \dot{q}^T M(q)\ddot{q} + \frac{1}{2}\dot{q}^T \dot{M}(q)\dot{q} + S_t\dot{S}_t \tag{22}$$

Replacing $\dot{S}_t$ by its expression, we get:

$$\dot{V} = \dot{q}^T\left[-\frac{\beta s}{\alpha r}\dot{e}^{\,2-r/s} - \frac{\hat{F}-\ddot{q}_d}{\alpha} - \frac{K}{\alpha}\,\mathrm{sign}(S_t) - C(q,\dot{q})\dot{q}\right] + \frac{1}{2}\dot{q}^T \dot{M}(q)\dot{q} + S_t\left[\frac{1}{\beta}\frac{r}{s}x_2^{(r/s)-1}\left(e_{est} - K\mathrm{sign}(S_t)\right)\right] \tag{23}$$

$$\dot{V} = \dot{q}^T\left[-\frac{\beta s}{\alpha r}\dot{e}^{\,2-r/s} - \frac{\hat{F}-\ddot{q}_d}{\alpha} - \frac{K}{\alpha}\,\mathrm{sign}(S_t)\right] + \frac{1}{2}\dot{q}^T\left[\dot{M}(q) - 2C(q,\dot{q})\right]\dot{q} + S_t\left[\frac{1}{\beta}\frac{r}{s}x_2^{(r/s)-1}\left(e_{est} - K\mathrm{sign}(S_t)\right)\right] \tag{24}$$

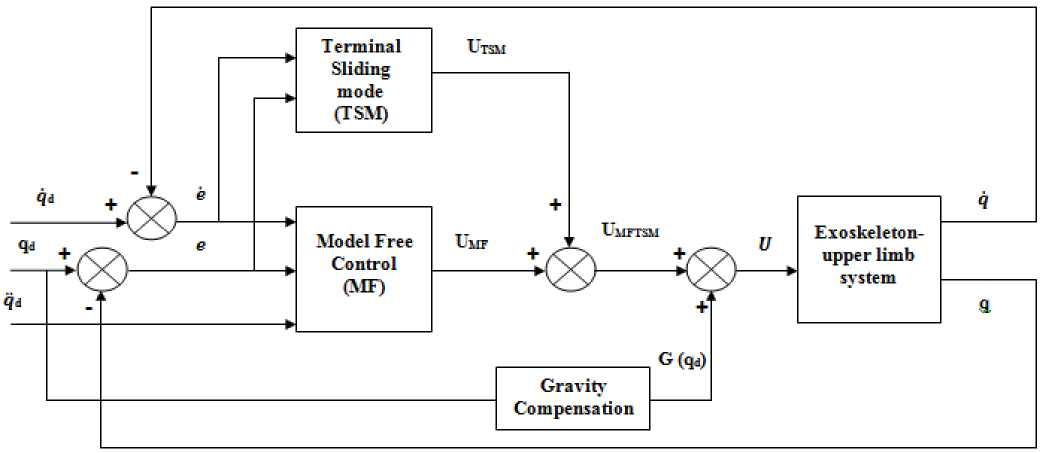

Fig. 4 The MF TSM with gravity compensation block diagram

As the inertia matrix and the Coriolis matrix are asymmetric, that is to say that they satisfy the following relation [31], [2]:

$$\dot{q}^T\left[\dot{M}(q) - 2C(q,\dot{q})\right]\dot{q} = 0$$

We can eliminate the term $\frac{1}{2}\dot{q}^T\left[\dot{M}(q) - 2C(q,\dot{q})\right]\dot{q}$. So we get:

$$\dot{V} = -\dot{q}^T\left[\frac{\beta s}{\alpha r}\dot{e}^{\,2-r/s} + \frac{\hat{F}-\ddot{q}_d}{\alpha} + \frac{K}{\alpha}\,\mathrm{sign}(S_t)\right] + \frac{1}{\beta}\frac{r}{s}x_2^{(r/s)-1}$$

$$(S_t\, e_{est} - S_t\, K\, \mathrm{sign}(S_t)) \quad (25)$$

$$\dot{V} < - |\dot{q}|^T \frac{\beta s}{\alpha r}\, \dot{e}^{\,2- r/s} \frac{K}{\alpha} |\dot{q}|^T - \frac{1}{\beta} \frac{r}{s} K\, x_2^{\,(r/s)-1}\, |S|_t \quad (26)$$

As:

- r and s are positive odd integers;
- $1 < r/s < 2$, then $x_2^{(r/s)-1} > 0$ for tt $x_2 \neq 0$ and $\dot{e}^{\,2- r/s} > 0$;
- K, β and α are positive.

So, for $x_2 \neq 0$, we have $\dot{V} < 0$.

IV. Robustness Analysis

The robustness of a system is defined as the stability of its performance in presence of disturbances. The robustness test is important in order to identify the operational factors which are not necessarily studied during the development phase of the method, but which could have an influence on the results, and therefore anticipate the problems that may arise at the time of the application of the method.

In this part, we will study the robustness of the considered system in presence of matched disturbances using Monte Carlo and H∞ methods.

A. Monte Carlo

This method is applied in different fields like finance, telecommunication, physical engineering, biology, social sciences [33], [32]. It is a powerful and very general mathematical tool which has earned it a wide range of applications. It is used to study the effects of parameters on stability properties.

The Monte Carlo method uses exhaustive and repeated simulations, where a specific value for each independent parameter of a model is drawn randomly from a given range of values, and then the output is computed. It constitutes a powerful and very general mathematical tool which has earned a wide range of applications [3].

The Monte Carlo method is done according to the following steps:

- Identifying and characterizing the uncertain parameters in the model.
- Sampling and randomly generation tests according to the identified probabilistic laws.
- The propagation of the uncertainty defined by the dataset resulting from step 2 will be done.
- The identification of the output set.
- A statistical analysis of the set results corresponding to the data set.
- Analyzing the convergence of the distribution of the model output.

B. H∞ Methods

H∞ methods are developed in order to synthesize algorithms to reach stabilization with assured performance and robustness.

H∞ techniques have the advantage over conventional control techniques in that they are easily applicable to problems involving multivariate systems with cross-coupling between channels.

This technique can be used to minimize the closed loop impact of a disturbance: depending on the formulation of the problem, the impact will be measured in terms of either stabilization or performance.

In this part, we applied a uniform random distribution to the system which will have the following form in presence of matched uncertainties [15], [17]:

$$\ddot{q} = (f(q, \dot{q}, t) + g(q)(u(t) + \delta_1) \quad (27)$$

where δ_1 presents matched uncertainties.

V. Simulation and Results

Simulation results are provided to prove the efficiency of gravity compensation applied to the proposed controller law.

The desired trajectories are given by:

- q_{1d}= sin (2*pi*t);
- q_{2d}= sin (2*pi*t);

The initial conditions of the real trajectories are:

- q (0) = [0; 0] ;
- $\dot{q}$ (0) = [0; 0];

Fig. 5 presents the measured and the desired trajectories of the released tests as well as the tracking trajectories errors in position and velocity. From this figure, we can clearly see the good position as well as velocity tracking of the desired trajectories in presence of matched uncertainties using the MF TSM controller with gravity compensation.

By calculating the Root-Mean-Square (RMS), the mean (Mean) and the standard deviation (Std), a robustness study is done in order to prove the controller performance when tracking the desired trajectories.

The RMS is calculated using the following expression:

$$q_{RMS} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} |q\,n|^2} \quad (28)$$

The Std can be expressed by:

$$\Sigma_q = \sqrt{E[q - E[q])^2]} = \sqrt{E[q^2] - E[q]^2} \quad (29)$$

and the sample mean is defined as:

$$\bar{q} = \frac{1}{m} \sum_{i=1}^{m} q_i \quad (30)$$

TABLE I
THE RESULTS SUMMARY OF THE ROBUSTNESS STUDY: THE RMS, THE ERROR AVERAGE VALUE AND THE STANDARD DEVIATION CALCULATION FOR EACH JOINT Q_1 AND Q_2 USING THE MF TSM CONTROL WITH GRAVITY COMPENSATION WHEN TRACKING THE DESIRED TRAJECTORIES IN POSITIONS IN PRESENCE OF MATCHED UNCERTAINTIES

		RMS [rad] 10^{-3}	Mean [rad] 10^{-3}	Std [rad] 10^{-3}
Monte Carlo	q_1	0.88	0.64	0.74
	q_2	0.92	0.86	0.82
H∞ method	q_1	1.05	0.89	1.01
	q_2	1.11	0.97	1.07

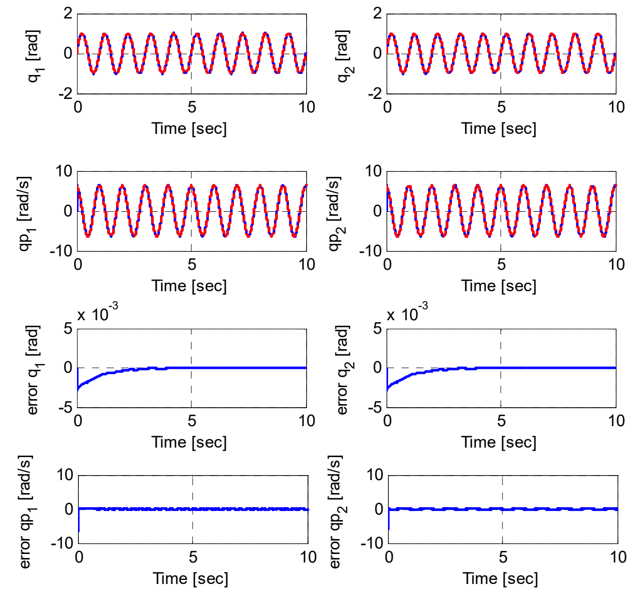

Fig. 5 Simulation results of q_1 and q_2 joints using the MF TSM with gravity compensation Control

Table I presents RMS, the error average value and the standard deviation calculation for each joint q_1 and q_2 using the MF TSM control gravity compensation when tracking the desired trajectories in positions in presence of matched uncertainties. It illustrates the robustness analysis using Monte Carlo and H∞ methods. Both of these methods approve the efficiency of the proposed controller in terms of performance and robustness.

VI. Conclusion

In this paper, the control, the stability study and the robustness analysis of an exoskeleton-upper limb system, used for rehabilitation, in presence of matched uncertainties, were presented. First, the modeling of the considered system was done. Then, a MF TSM algorithm with gravity compensation is developed. A robustness study using Monte Carlo and H∞ methods was done to analyze the performance of the exoskeleton-upper limb system in presence of matched uncertainties. Simulation results are provided to prove the performance and the robustness of the gravity compensation applied to the MF TSM when tracking the desired trajectories. As a future work, experimental results will be done when the exoskeleton is worn by the human upper limb.

References

[1] Andrew A, Amis PhD, CEng, Minech E, Part 1. Upper limb functions, Shoulder and Elbow, Current Orthopaedics, Volume 4, Issue 1, January 1990, Pages 21-26.

[2] M. W. Spong, M. Vidyasagar,*" Robot Dynamics and Control",* John Wiley & Sons, 1989.

[3] Laura Ryan Rayt And Robert F. Stengel,*" A Monte Carlo Approach to the Analysis of Control System Robustness", Automatica,* Vol. 29, No. 1, pp. 229-236, 1993.

[4] Ho Shing Lo∗, Sheng Quan Xie , 'Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects', Medical Engineering & Physics 34 (2012) 261–268

[5] G. Schmeisser and W. Seamone, "An Upper Limb Prosthesis-Orthosis Power and Control System with Multi-Level Potential," J. Bone Joint Surg. Am., vol. 55, pp. 1493–1501, 1973.

[6] Md Rasedul Islam, Christopher Spiewak, Mohammad Habibur Rahman and Raouf Fareh, 'A Brief Review on Robotic Exoskeletons for Upper Extremity Rehabilitation to Find the Gap between Research Porotype and Commercial Type', Advances in Robotics & Automation, 2017.

[7] R. A. R. C. Gopura, Kazuo Kiguchi, 'Mechanical Designs of Active Upper-Limb Exoskeleton Robots State-of-the-Art and Design Difficulties', IEEE 11th International Conference on Rehabilitation Robotics Kyoto International Conference Center, Japan, June 23-26, 2009.

[8] T. Laliberte, C. Gosselin, and D. Gao, "Closed-loop transmission routings for cartesian scara-type manipulators," in ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, 2010, pp. 281–290.

[9] M.-A. Lacasse, G. Lachance, J. Boisclair, J. Ouellet, and C. Gosselin, "On the design of a statically balanced serial robot using remote counterweights," Robotics and Automation (ICRA), 2013 IEEE International Conference on, May 2013, pp. 4189–4194.

[10] Y. Bouteraa and I. Ben Abdallah, Estimated Model-Based Sliding Mode Controller for an Active Exoskeleton Robot, Chapter 10: Applications of Sliding Mode Control, Decision and Control, October 2016, pp. 175-189.

[11] N. Jarassé, Contributions à l'exploitation d'exosquelettes actifs pour la rééducation neuromatrice, November 2011, pp. 17-26.

[12] H. Su, Z. Li, G. Li and Ch. Yang, EMG-Based Neural Network Control of an Upper-Limb Power-Assist Exoskeleton Robot., Conference of Proceedings of the 10th international conference on Advances in Neural Networks, July 2013.

[13] Sana Bembli, Nahla Khraief Haddad, Safya Belghith, "Robustness analysis of an upper limb exoskeleton controlled by sliding mode algorithm", The 1st International Congress for the Advancement of Mechanism, Machine, Robotics and Mechatronics Sciences (ICAMMRMS-2017), Beirut LEBANON, October 17 - 19, 2017.

[14] Sana Bembli, Nahla Khraief Haddad, Safya Belghith," Robustness analysis of an upper-limb exoskeleton controlled by an adaptive sliding mode", The 5th International Conference on Control Engineering &Information Technology (CEIT-2017), December 17-19, 2017 Sousse – Tunisia.

[15] Sana Bembli, Nahla Khraief Haddad, Safya Belghith, "Robustness analysis of an upper-limb exoskeleton using Monte Carlo simulation", The 2nd International Conference on Advanced Systems and Electrical Technologies (IC_ASET), 22-25 March 2018, Hammamet, Tunisia.

[16] Sana Bembli, Nahla Khraief Haddad, Safya Belghith, "Adaptive sliding mode control with gravity compensation: Application to an upper-limb exoskeleton system", The Fifth International Francophone Congress of Advanced Mechanics (IFCAM 2018), Faculty of Engineering - Lebanese University, Lebanon, October 31 - November 2,2018.

[17] Sana Bembli, Nahla Khraief Haddad, Safya Belghith, "Computer aided decision model to control an exoskeleton-upper limb system", The 3rd International Conference on Advanced Systems and Electrical Technologies (IC_ASET), 19- 22 March 2019, Hammamet, Tunisia.

[18] Sana Bembli, Nahla Khraief Haddad, Safya Belghith, "A Terminal sliding mode control using EMG signal: Application to an exoskeleton-upper limb system", 16th International Conference on Informatics in Control, Automation and Robotics (ICINCO-2019), Prague, 29-31 July, 2019.

[19] Romain Bourdais, Michel Fliess, Cédric Join, and Wilfrid Perruquetti, "*Towards a model-free output tracking of switched nonlinear systems",* In NOLCOS 2007 - 7th IFAC Symposium on Nonlinear Control Systems, Pretoria, South Africa, 2007.

[20] Michel Fliess, Cédric Join,MamadouMboup, and Hebertt Sira Ramirez, "*Vers une commande multivariable sans modèle* ", Conférence internationale francophone d'automatique (CIFA 2006), Bordeaux, France, 2006.

[21] Brigitte D'Andrea Novel, Michel Fliess, Cédric Join, Hugues Mounier, and Bruno Steux," *A mathematical explanation via "intelligent" PID controllers of the strange ubiquity of PIDs",*. In 18th Mediterranean Conference on Control and Automation, MED'10, Marrakech Morocco, 2010.

[22] Michel Fliess and Cédric Join., "*Intelligent PID controllers*"., 16th Mediterranean Conference on Control and Automation, Ajaccio, France, 2008.

[23] Michel Fliess and Cédric Join. *"Model-free control and intelligent PID controllers: towards a possible trivialization of nonlinear control",* 15th IFAC Symposium on System Identification (SYSID 2009), Saint-Malo, France, 2009.
[24] Wei He, IEEE, Zhijun Li , Yiting Dong , and Ting Zhao, "Design and Adaptive Control for an Upper Limb Robotic Exoskeleton in Presence of Input Saturation", IEEE Transactions On Neural Networks And Learning Systems, April , 2018.
[25] Vigen Arakelian, "Gravity compensation in robotics", Advanced Robotics, 2016 VOL. 30, NO. 2, 79–96.
[26] Satoshi Ito, Shingo Nishio, Yuuki Fukumoto, Kojiro Matsushita, and Minoru Sasaki, "Gravity Compensation and Feedback of Ground Reaction Forces for Biped Balance Control", Applied Bionics and Biomechanics Volume 2017, Article ID 5980275, 16 pages.
[27] Julien Boisclair, Pierre-Luc Richard, Thierry Laliberte, and Clement Gosselin, "Gravity compensation of robotic manipulators using cylindrical Halbach arrays", Journal Of Latex Class Files, Vol. 13, No. 9, September 2014.
[28] V. Behnamgol and A. R. Vali., "Terminal Sliding Mode Control for Nonlinear Systems with Both Matched and Unmatched Uncertainties", Iranian Journal of Electrical & Electronic Engineering, Vol. 11, No. 2, June 2015.
[29] Chaoxu Mu and Haibo He, "Dynamic Behavior of Terminal Sliding Mode Control", IEEE Transactions on Industrial Electronics, Vol. 65, No. 4, April 2018.
[30] Yuqiang Wu, Xinghuo Yu and Zhihong Man, "Terminal sliding mode control design for uncertain dynamic systems", Systems & Control Letters 34 (1998) 281–287.
[31] F. L. Lewis, C. T. Abdallah, D. M. Dawson, *"Control of robot manipulators",* NY 10022, 1993.
[32] Gersende Fort, *"Méthodes de Monte Carlo Et Chaînes de Markov pour la simulation ",* Mémoire présenté pour l'obtention de l'Habilitation à Diriger les Recherches, Novembre 2009.